

**Final Report**

**Contract Number: DAAH04-94-G-0051**

**Ignition in Convective-Diffusive Systems**

**Submitted By:**

**Chung K. Law  
Department of Mechanical and Aerospace Engineering  
Princeton University  
Princeton, NJ 08544**

**Phone: 609-258-5178**

**Fax: 609-258-6233**

**E-Mail: cklaw@princeton.edu**

**For Consideration By:**

**Dr. David M. Mann  
Army Research Office**

## Introduction

Motivation for this program stems from the Army's interest in understanding and increasing the performance of diesel engines which serve as the main powerplant for its tactical vehicles. In a diesel engine liquid fuel is injected into the combustion chamber as the gas within it is compressed. The fuel spray vaporizes and mixes with the air, and ignition eventually occurs as the chamber environment attains a sufficiently high temperature and pressure. Since ignition initiates the entire combustion process, a good understanding of the ignition process is crucial to the overall performance of the engine in terms of its combustion efficiency as well as the knock and emission characteristics.

The ignition event is clearly controlled by the chemical reactions of fuel oxidation and the fluid mechanics of convective and diffusive transport. Since each of these two components is a complex process, most of previous studies have simplified the problem by using either one-step overall reactions or by studying ignition in a homogeneous medium, which respectively simplifies the chemistry and the fluid mechanics. Thus there is the need to understand and quantify the coupled influences of the chemical and physical processes on ignition.

In response to such a need, in the present program we have systematically studied the ignition of fuels in controlled diffusive environments of fuel/oxidizer mixing layers. Most of the studies involved the counterflow configuration created by impinging a cold fuel jet against a hot oxidizer jet, although studies were also conducted for the parallel mixing layer to simulate the practical situation of flame stabilization. The study utilized laser-based experimentation, computation with detailed chemistry and transport, and mathematical analysis with activation energy asymptotics. The study has qualitatively identified some very unique ignition phenomena, and quantitatively determined the states of ignition in terms of the fuel, the heated air temperature, the system pressure, and the strain rate of the flow. The following are highlights of the findings. Details of the results can be found in our annual reports as well as the journal articles listed.

## Highlights of Accomplishments

1. Multiple ignition, extinction, and stability of nonpremixed hydrogen/air flames:
  - Demonstrated experimentally the existence of triple stable stationary states, and two-staged ignition and extinction (Fig. 1).
  - First ignition is kinetically-dominated; second ignition thermally-assisted (Fig. 2).
2. Experimental and computational studies of nonpremixed hydrocarbon ignition under variable pressure, flow intensity, and fuel dilution:
  - Methane
  - Ethane
  - Propane
  - n-Butane and isobutane.
  - \* Identified common ignition characteristics:
    - Hot ignition preceded by cool flame type chemiluminescence ("two-staged ignition), except at high pressures (Fig. 3).
    - Based on ethane modeling, first ignition is kinetically-dominated and involves low-to-intermediate temperature chemistry; flame ignition is thermally assisted and dominated by high-temperature reactions.
    - First ignition temperature is less sensitive to changes in external parameters, such as flow straining or fuel dilution (Figs. 3 and 4).
    - Ignitability enhanced by increasing fuel concentration and pressure, or by decreasing flow strain rate (Figs. 3-5).
    - n-Butane is easier to ignite than isobutane (Fig. 6).
  - \* Butane shows clear transition to low temperature ignition at high pressures (Fig. 7).
  - \* Nonpremixed ignition vs. auto-ignition (Fig. 8):
    - Higher temperature required for nonpremixed ignition.
    - Reversed trend, due to fuel diffusivity reduction.
3. Ignition enhancement by hydrogen addition:
  - Carbon monoxide/hydrogen (Fig. 9)
  - Methane/hydrogen (Fig. 10)

4. Analytical studies of hydrogen/air nonpremixed ignition:
  - Derived reduced kinetic models for ignition.
  - Tested the validity of steady-state approximations in premixed and nonpremixed configurations (Fig. 11).
  - Quantified the relative roles of chemistry and heat release at ignition (Fig. 12).
  
5. Unsteady ignition phenomena:
  - \* System response depends on the frequency and amplitude of imposed oscillations:
    - At low frequencies, the transient response follows the steady-state solution (Fig. 13).
    - At high frequencies, the system no longer responds to imposed oscillations (Fig. 14).
    - Transient ignition behaves quasi-steadily at low frequencies (Fig. 15).
    - Oscillation retards ignition at high frequencies; increasingly larger amplitudes are required to effect ignition (Figs. 15 and 16).
    - Cut-off frequency exists beyond which ignition cannot occur by increasing the oscillation amplitude (Fig. 17).
    - Ignitability depends on whether the excursion time exceeds the ignition delay time (Figs. 18 and 19).

### Journal Publications (1994-1997)

1. "Asymptotic Analysis of Ignition in Nonpremixed Counterflowing Hydrogen versus Heated Air," by S.R. Lee and C.K. Law, *Combustion Science and Technology*, Vol. 97, pp. 377-389 (1994).
2. "Analysis of Thermal Ignition in the Supersonic Mixing Layer," by H.G. Im, B.H. Chao, J.K. Bechtold, and C.K. Law, *AIAA Journal*, Vol. 32, pp. 341-349 (1994).
3. "The Role of Kinetic versus Thermal Feedback in Nonpremixed Ignition of Hydrogen versus Heated Air," by T.G. Kreutz, M. Nishioka, and C.K. Law, *Combustion and Flame*, Vol. 99, pp. 758-766 (1994).
4. "An Experimental Study of Ignition in Nonpremixed Counterflowing Hydrogen versus Heated Air," by C.G. Fotache, T.G. Kreutz, D.L. Zhu, and C.K. Law, *Combustion Science and Technology*, Vol. 109, pp. 373-394 (1995).
5. "A Flame-Controlling Continuation Method for Generating S-Curve Responses with Detailed Chemistry," by M. Nishioka, C.K. Law, and T. Takeno, *Combustion and Flame*, Vol. 104, pp. 328-342 (1996).
6. "Ignition in Nonpremixed Counterflowing Hydrogen versus Heated Air: Computational Study with Detailed Chemistry," by T.G. Kreutz and C.K. Law, *Combustion and Flame*, Vol. 104, pp. 157-175 (1996).
7. "Ignition in the Supersonic Hydrogen/Air Mixing Layer with Reduced Mechanisms," by H.G. Im, B.T. Helenbrook, S.R. Lee, and C.K. Law, *Journal of Fluid Mechanics*, Vol. 322, pp. 275-296 (1996).
8. "Ignition of Hydrogen and Oxygen in Counterflow at High Pressures," by B.T. Helenbrook and C.K. Law, *Twenty-Sixth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, pp. 815-822 (1996).
9. "A Numerical Study of Ignition in the Supersonic Hydrogen/Air Laminar Mixing Layer," by M. Nishioka and C.K. Law, *Combustion and Flame*, Vol. 108, pp. 199-219 (1997).
10. "Ignition of Counterflowing Methane versus Heated Air under Reduced and Elevated Pressures," by C.G. Fotache, T.G. Kreutz, and C.K. Law, *Combustion and Flame*, Vol. 108, pp. 442-470 (1997).
11. "Ignition of Oscillatory Counterflowing Nonpremixed Hydrogen against Heated Air," by C. J. Sung and C.K. Law, *Combustion Science and Technology*, Vol. 129, pp. 347-360 (1997).
12. "Ignition in a Counterflowing Non-Premixed CO/H<sub>2</sub>-Air System," by J.Y.D. Trujillo, T.G. Kreutz and C.K. Law, *Combustion Science and Technology*, Vol. 127, pp. 1-27 (1997).

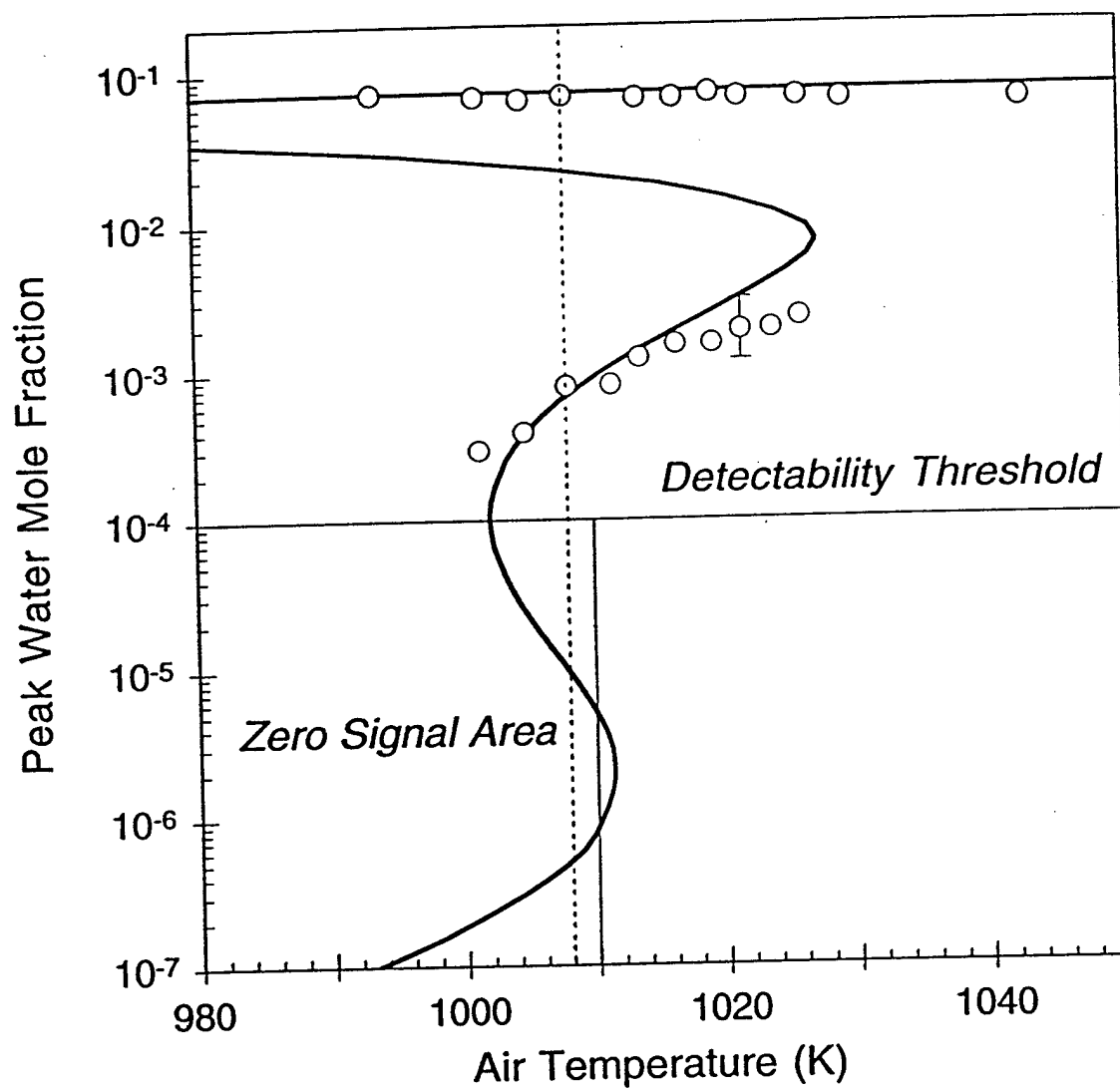


Figure 1

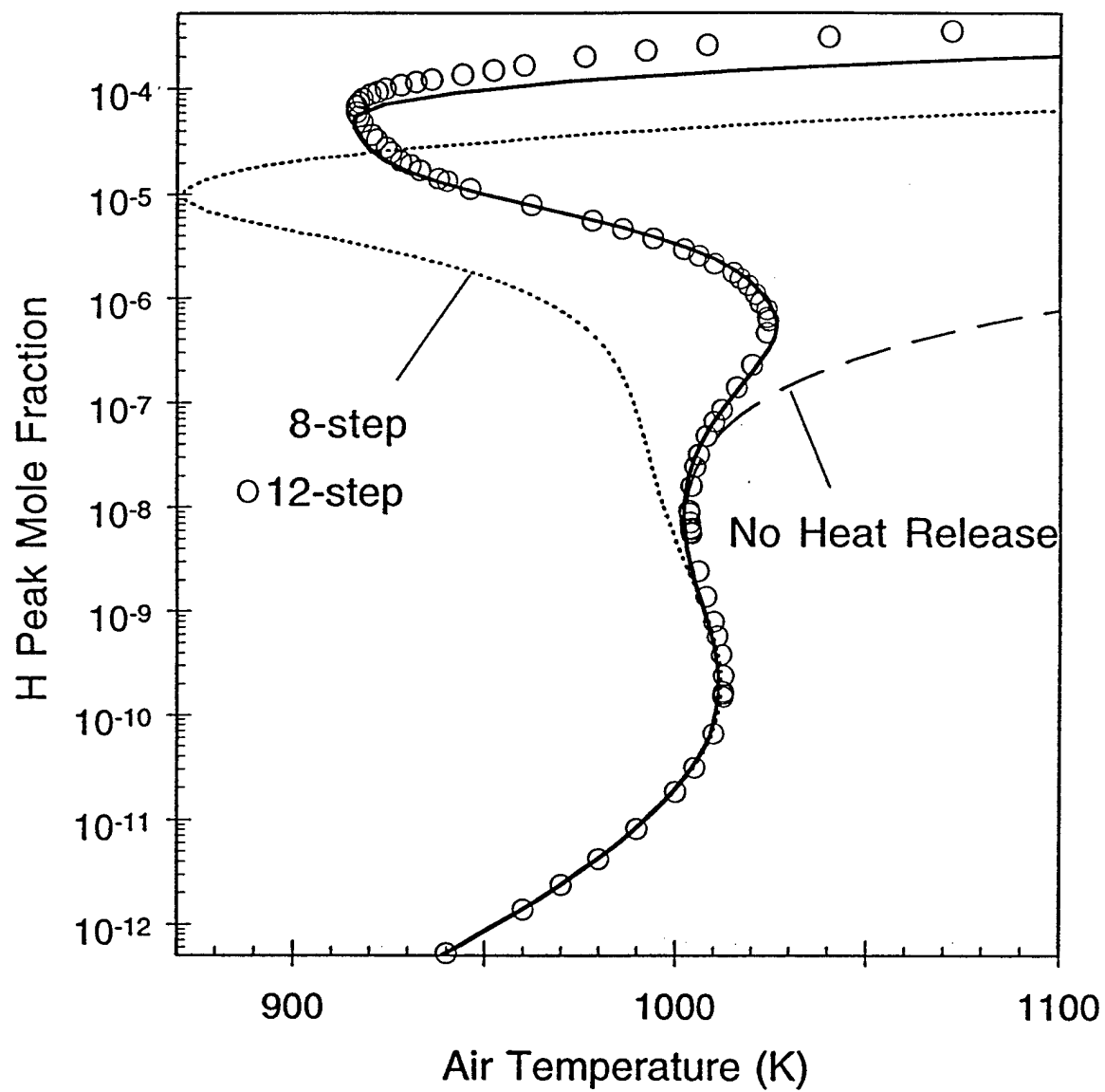


Figure 2

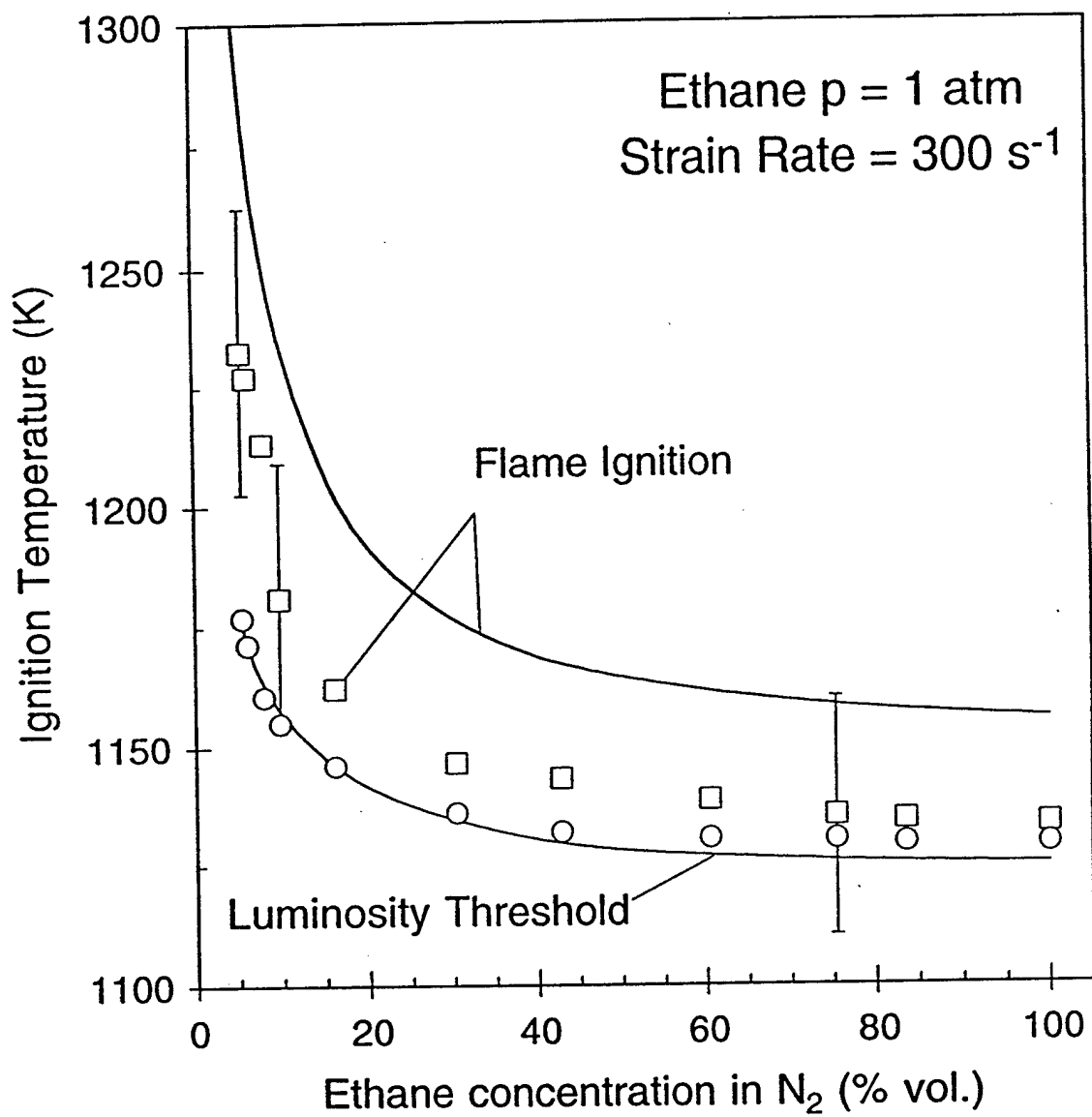


Figure 3

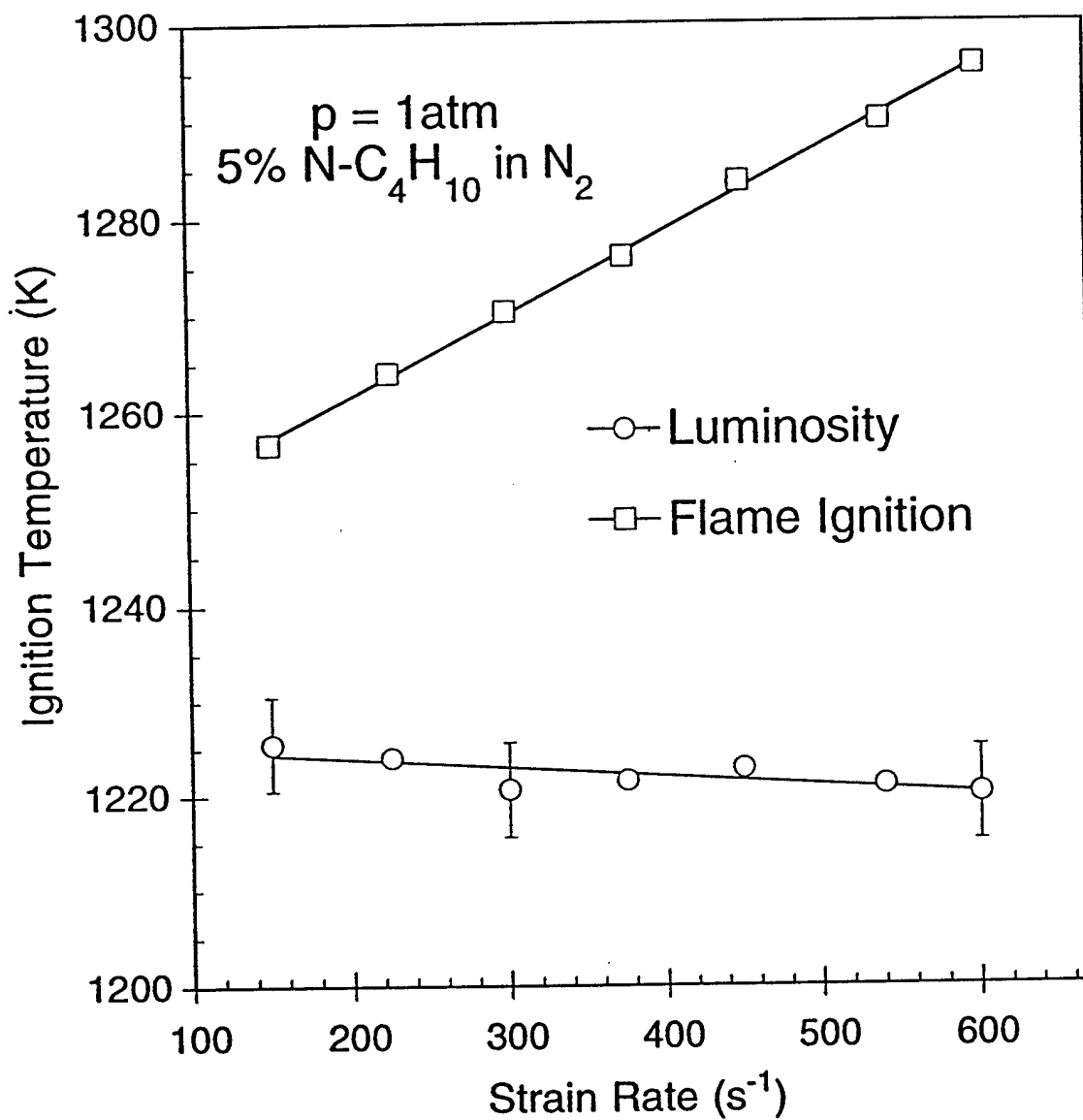


Figure 4

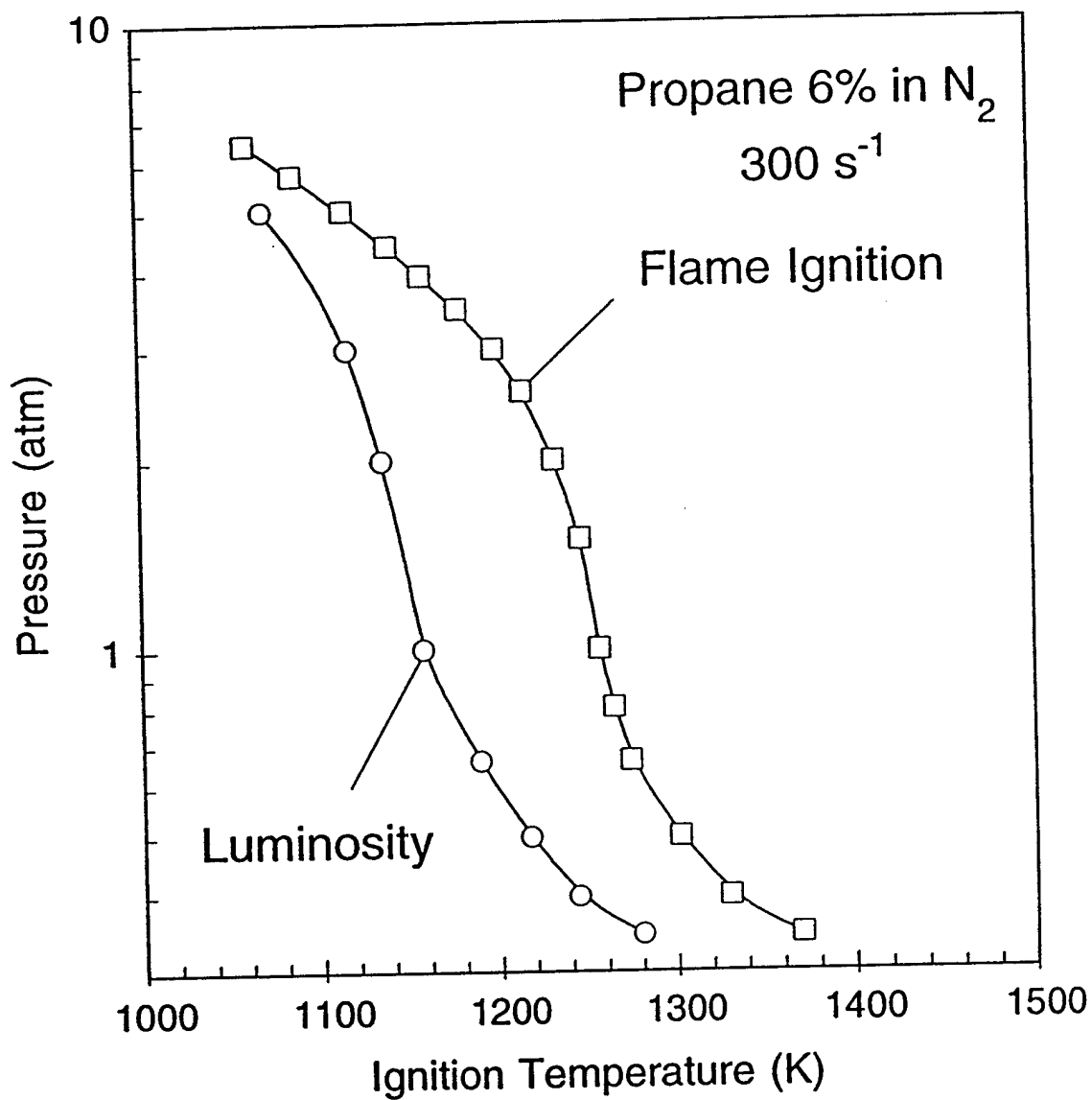


Figure 5

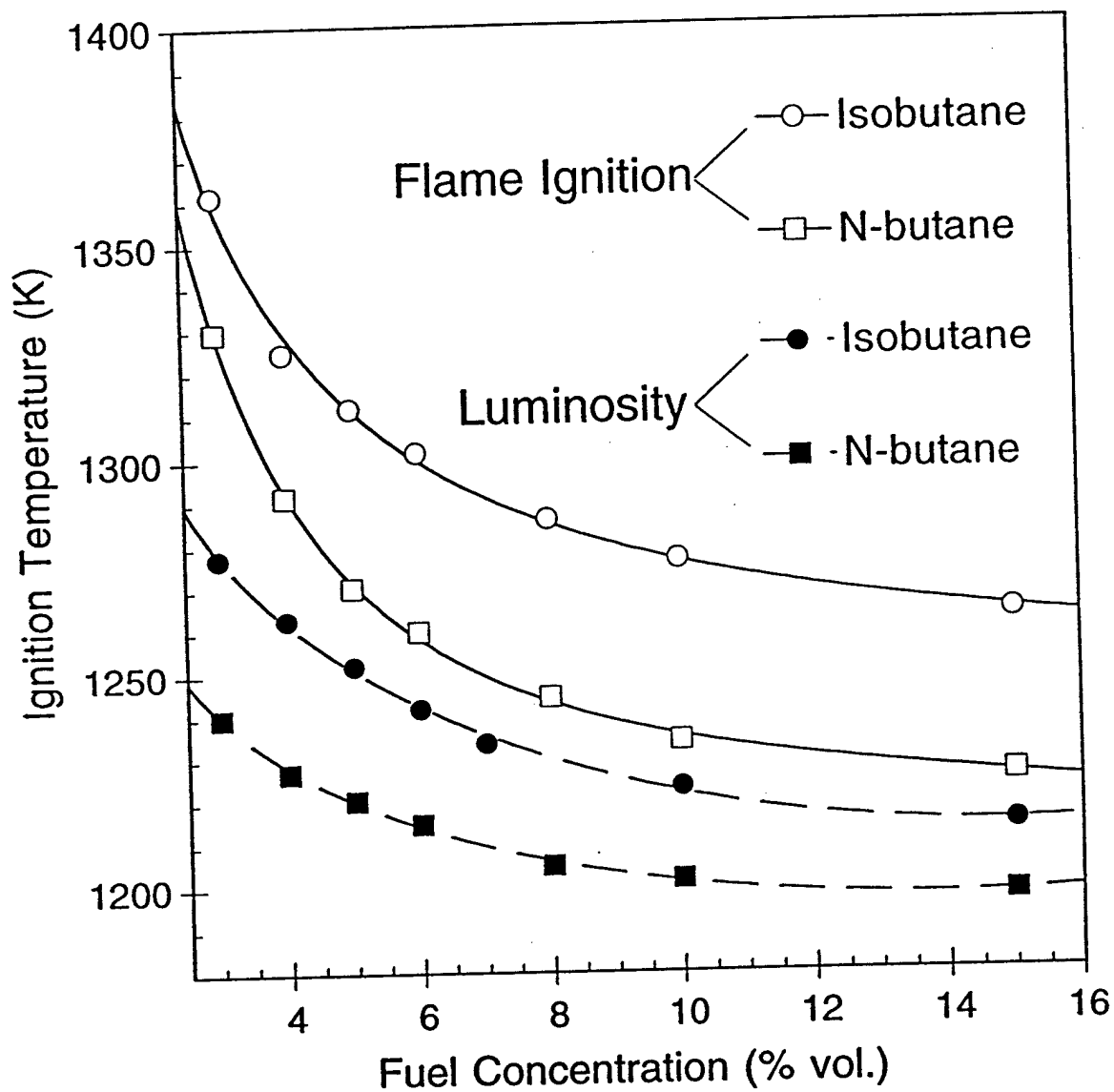


Figure 6

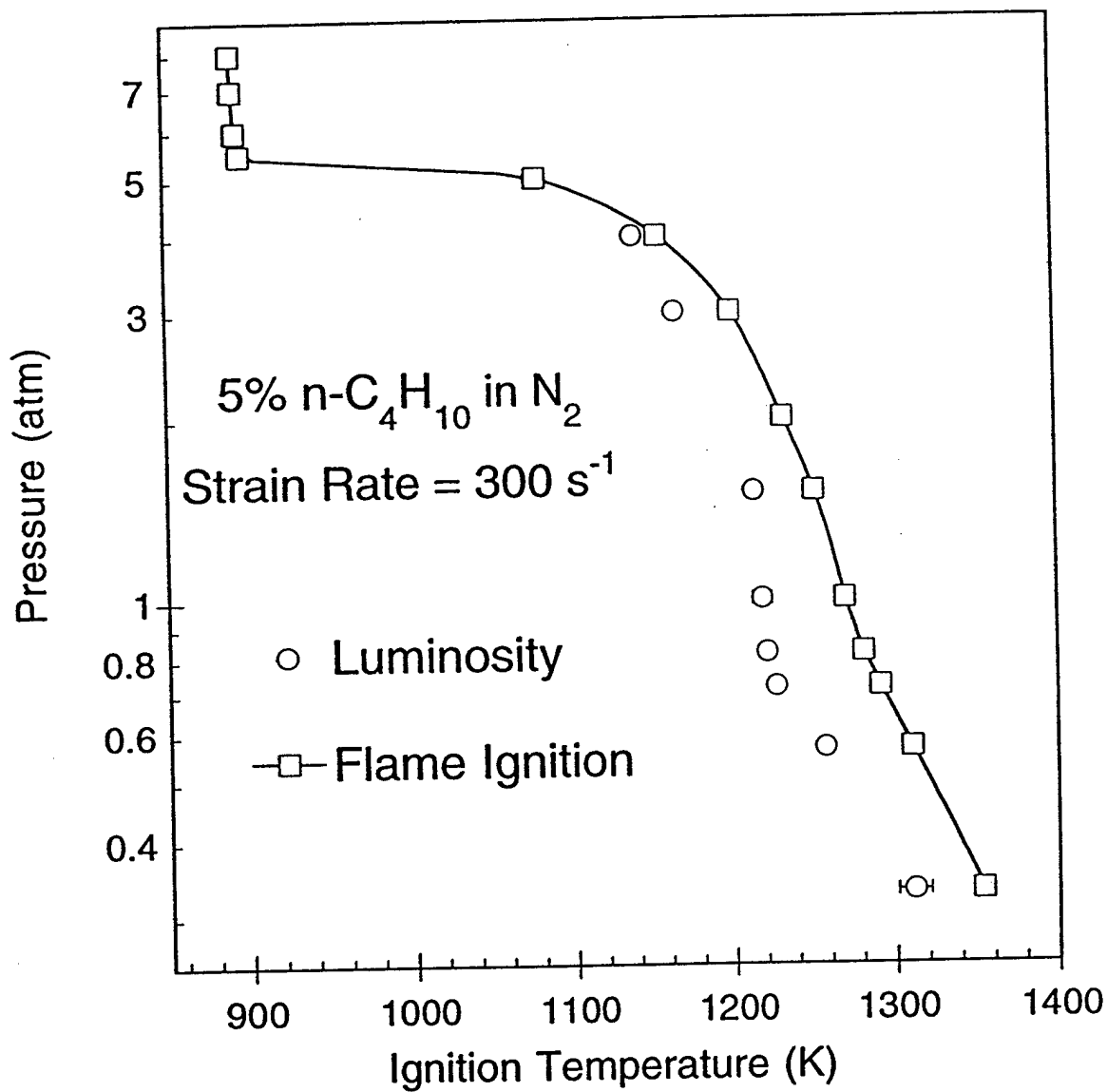


Figure 7

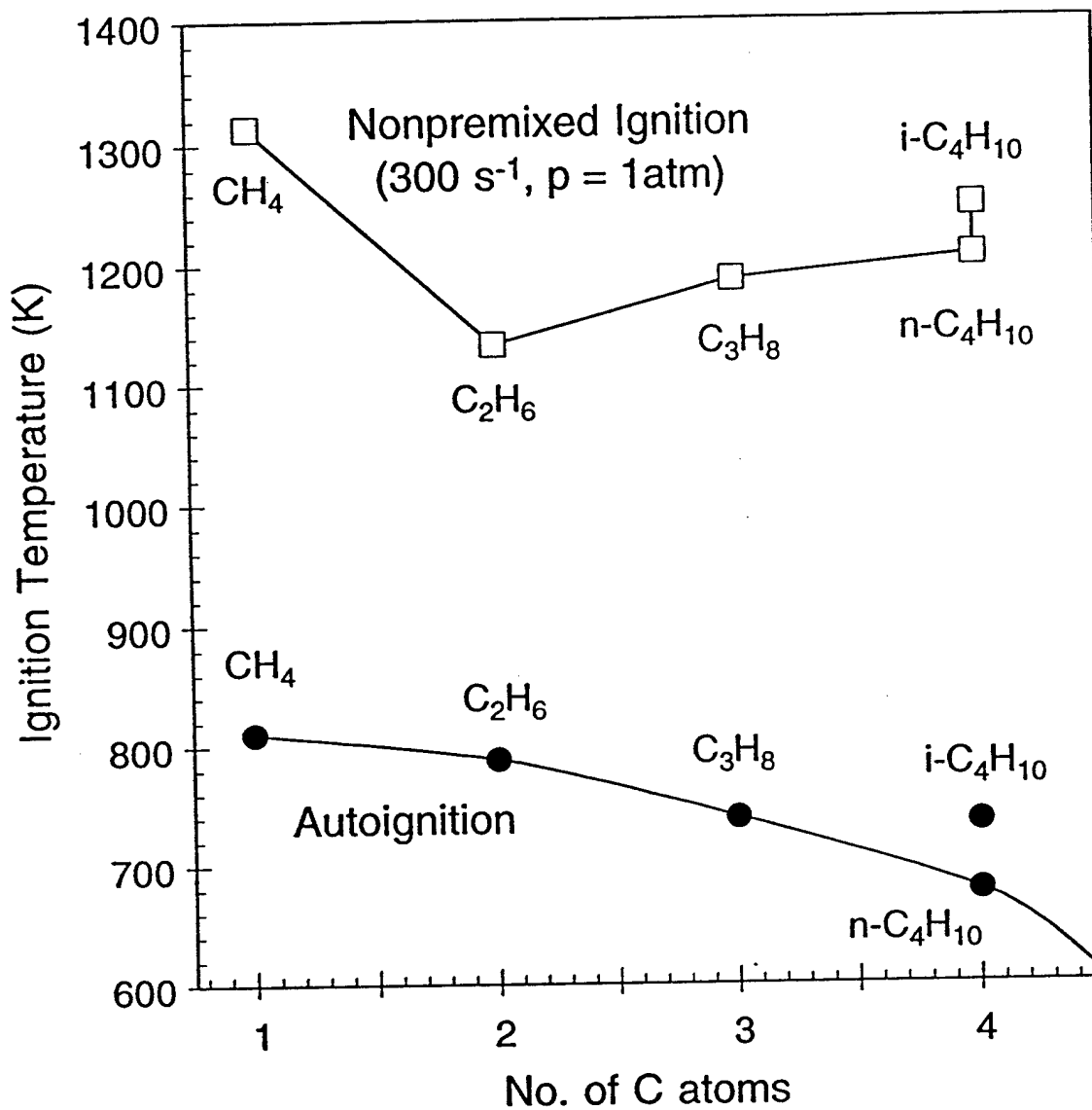


Figure 8

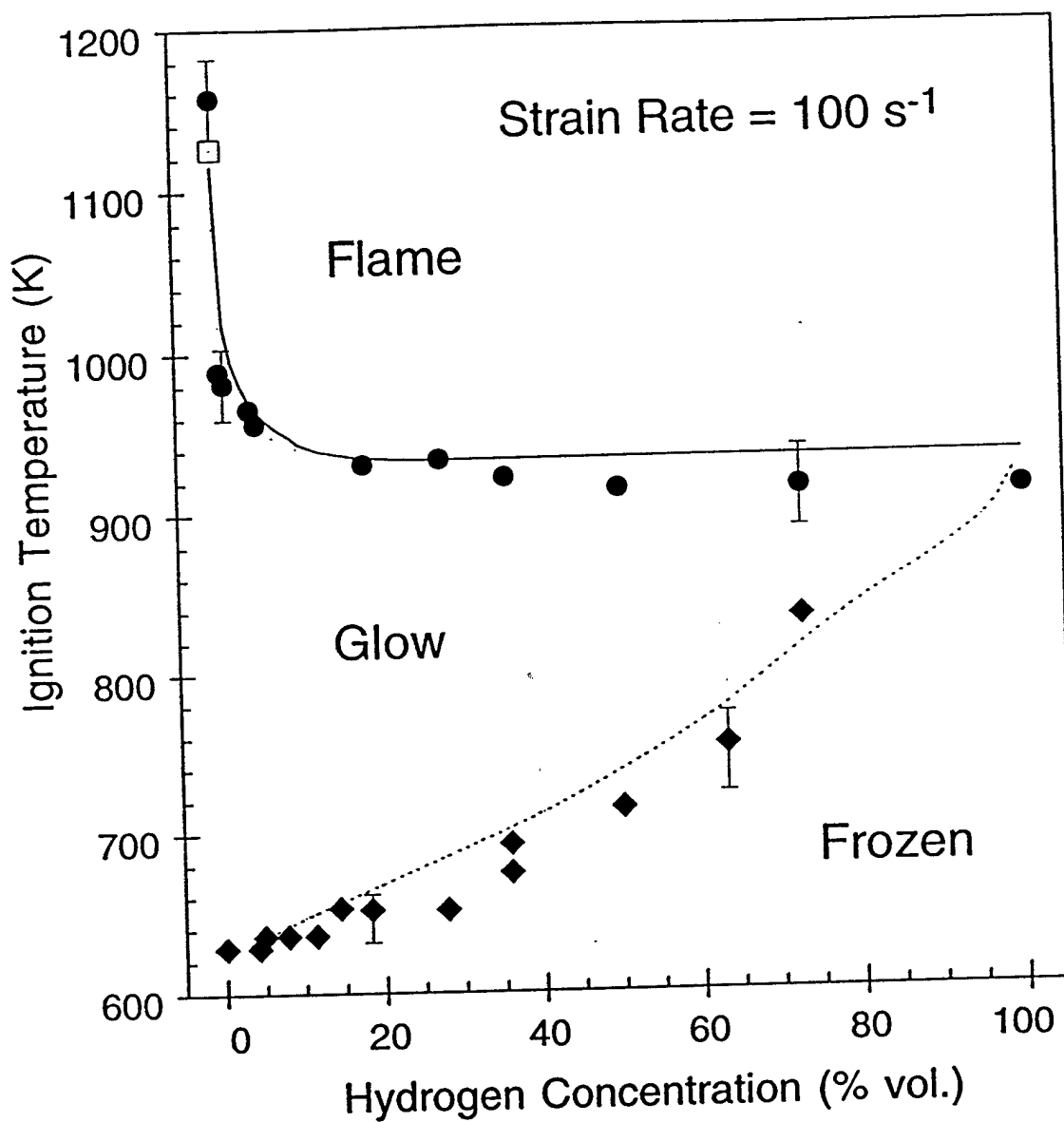


Figure 9

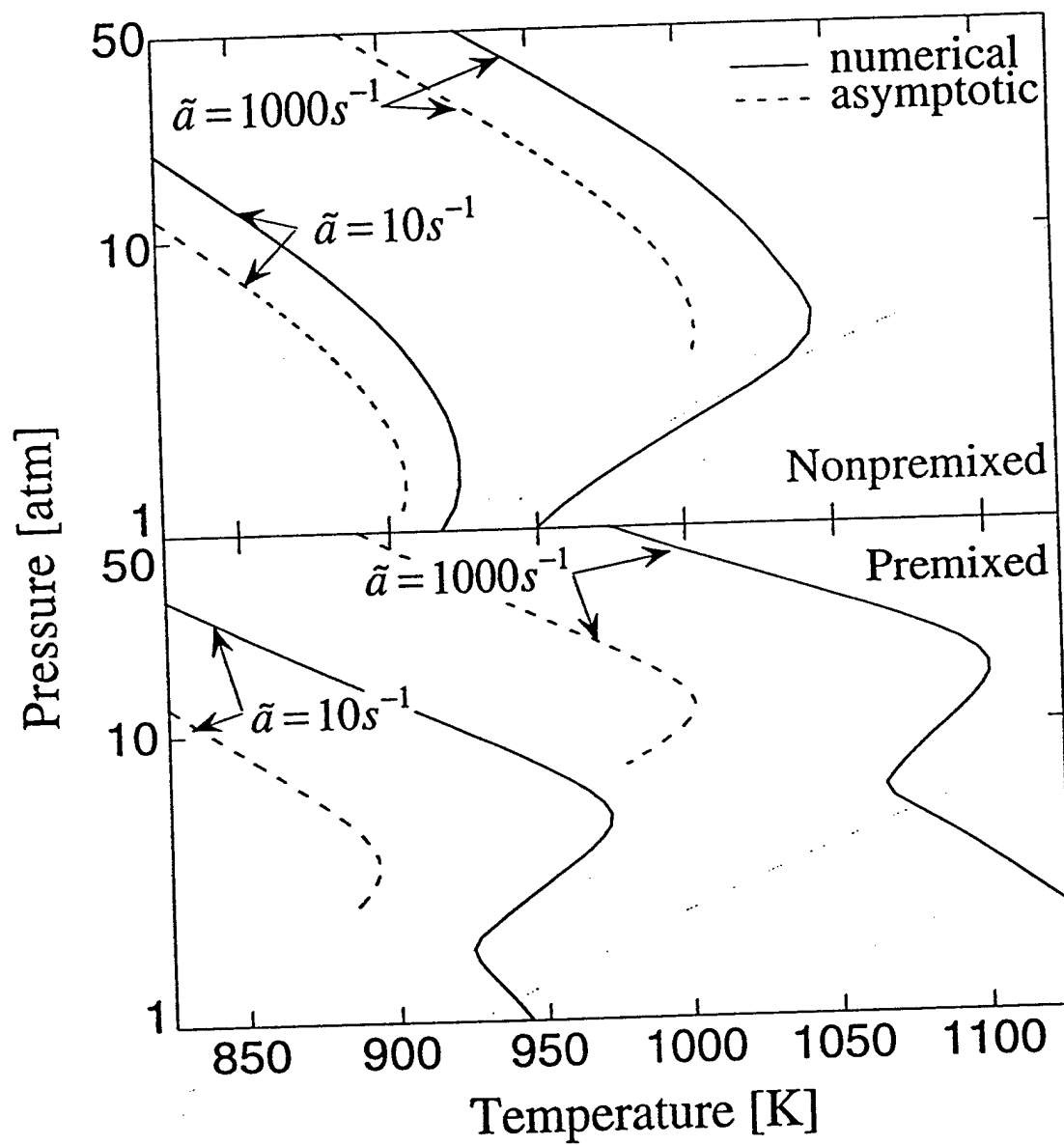


Figure 11

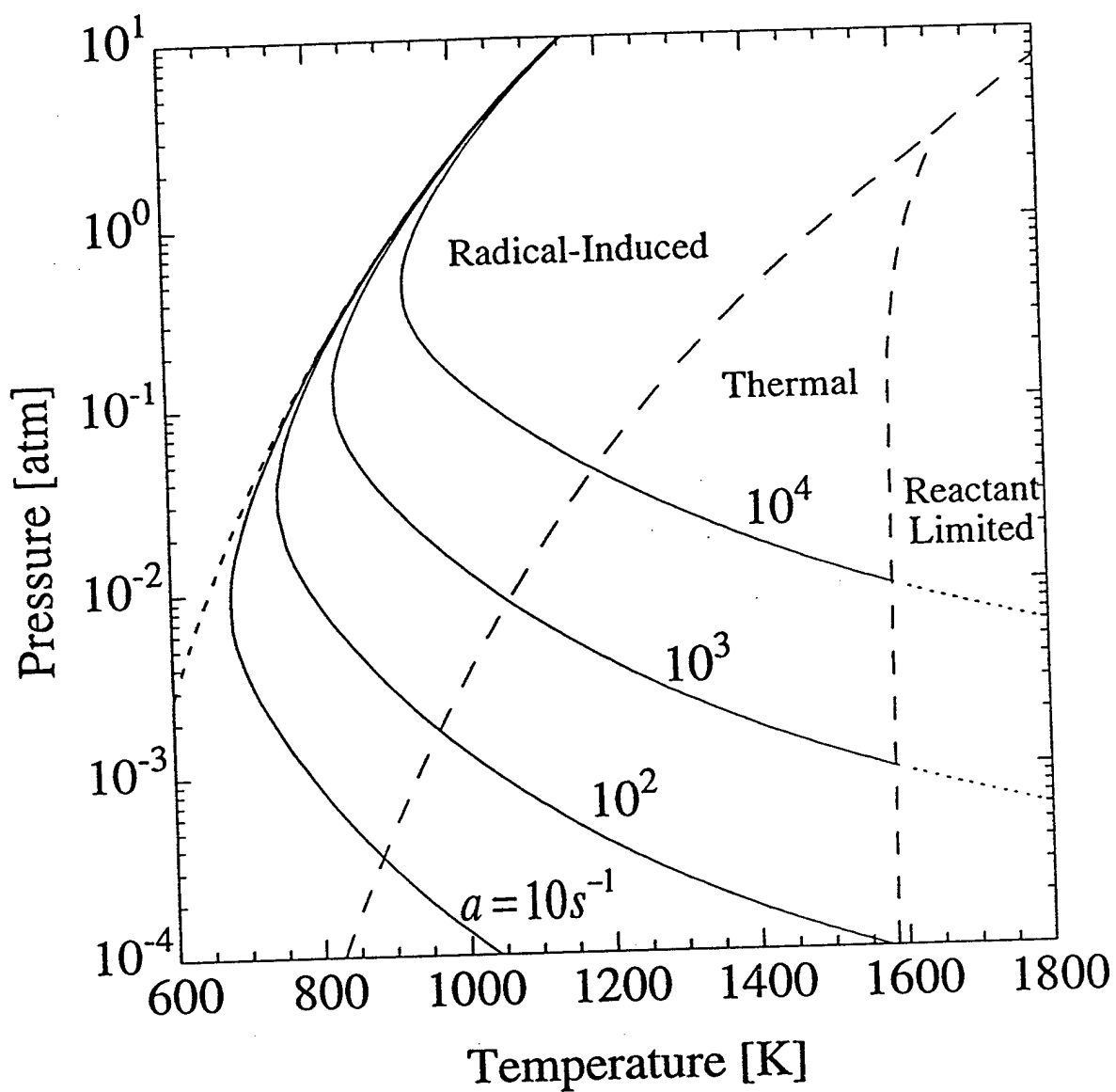


Figure 12

60%H<sub>2</sub>, T<sub>air</sub>=935 K, A=0.03

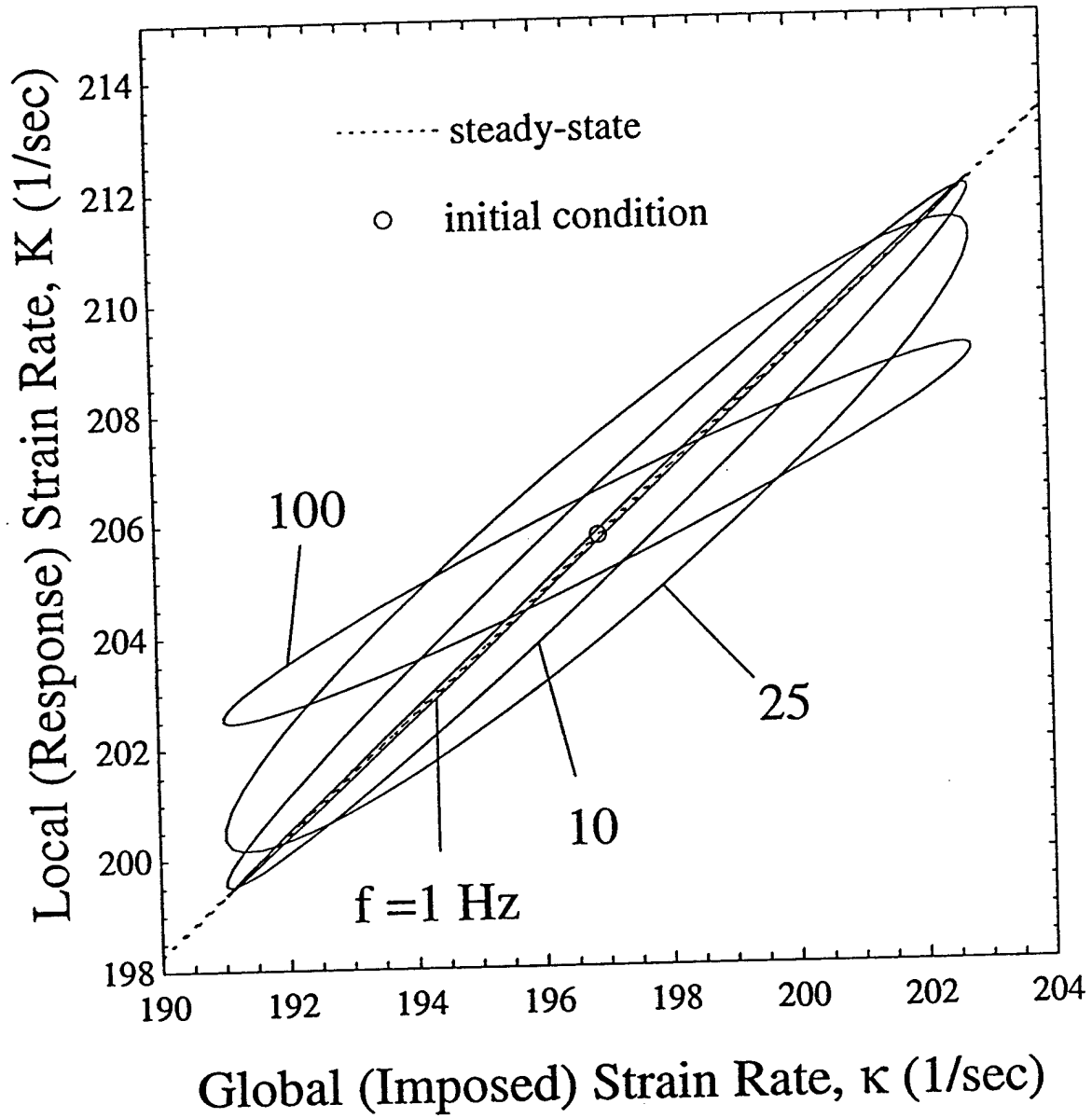


Figure 13

60%H<sub>2</sub>, T<sub>air</sub>=935 K, A=0.03

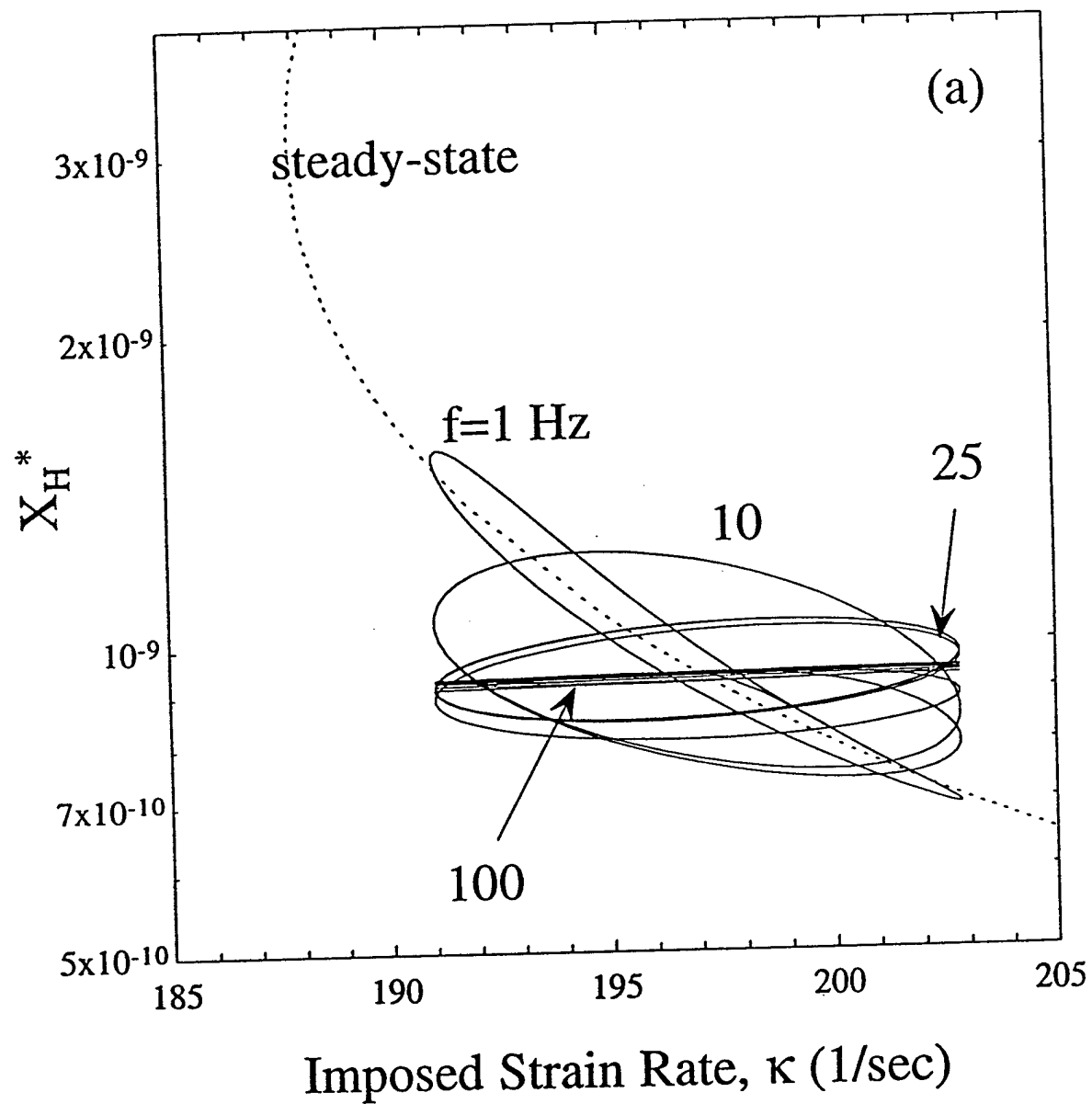


Figure 14

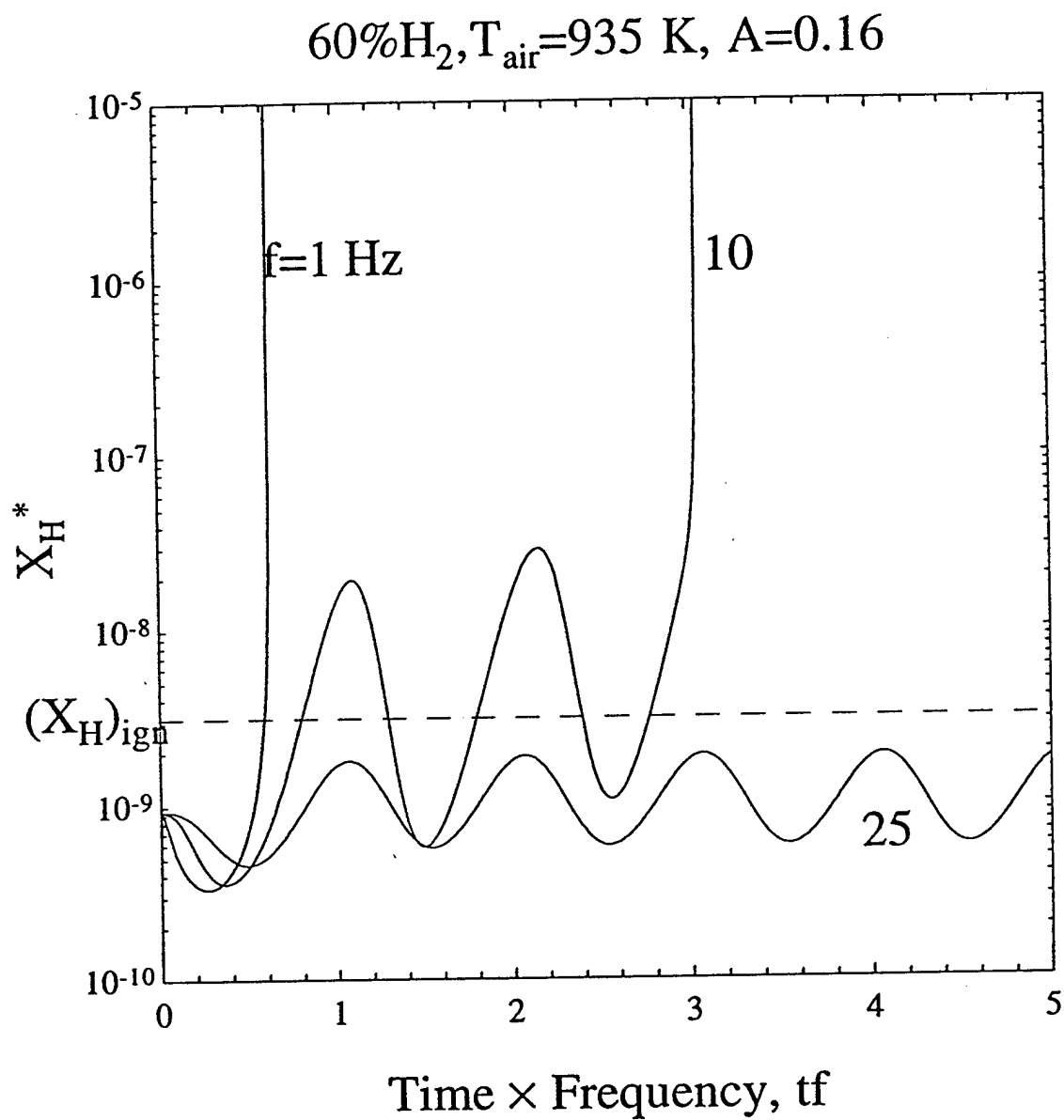


Figure 15

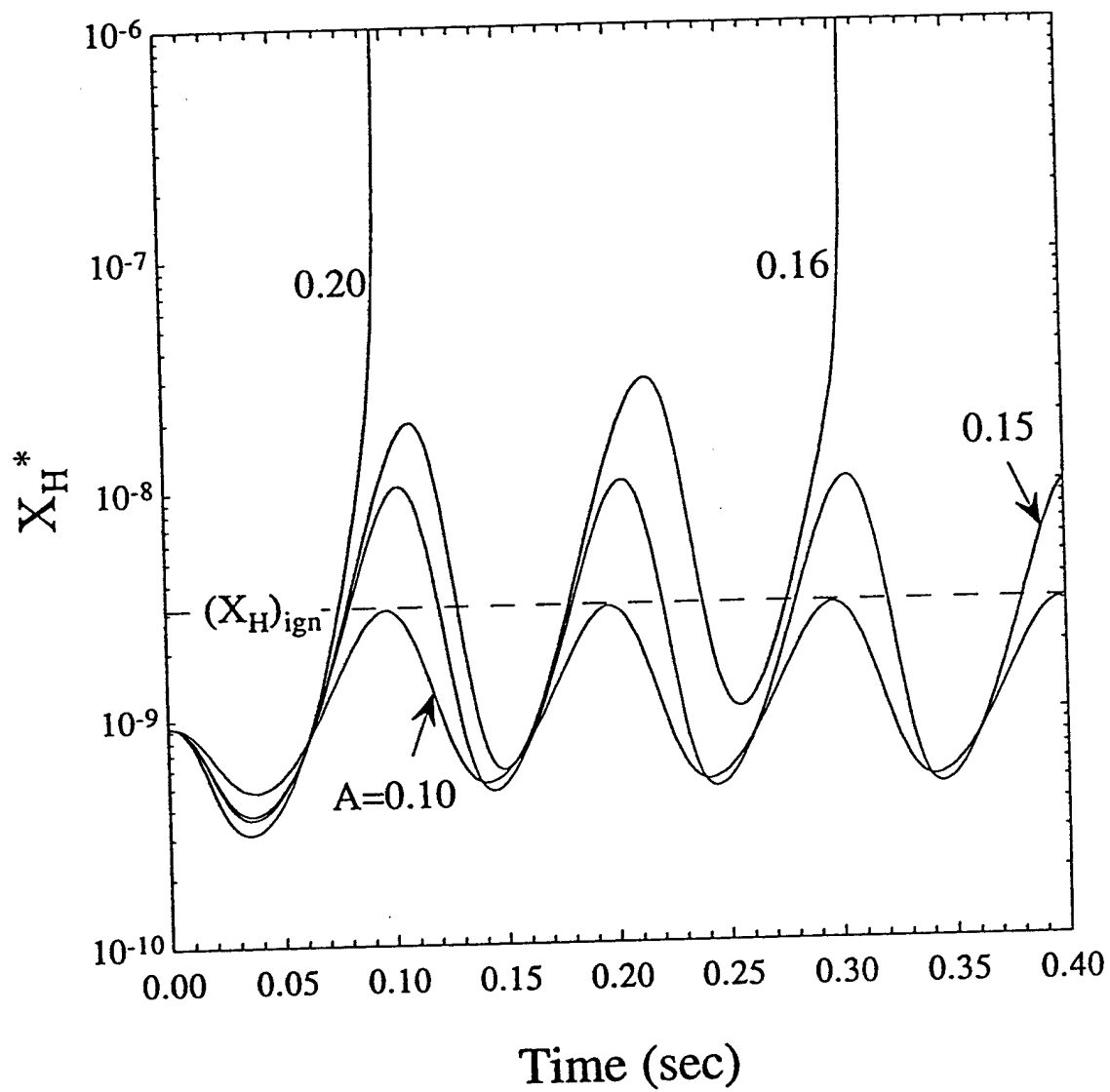


Figure 16

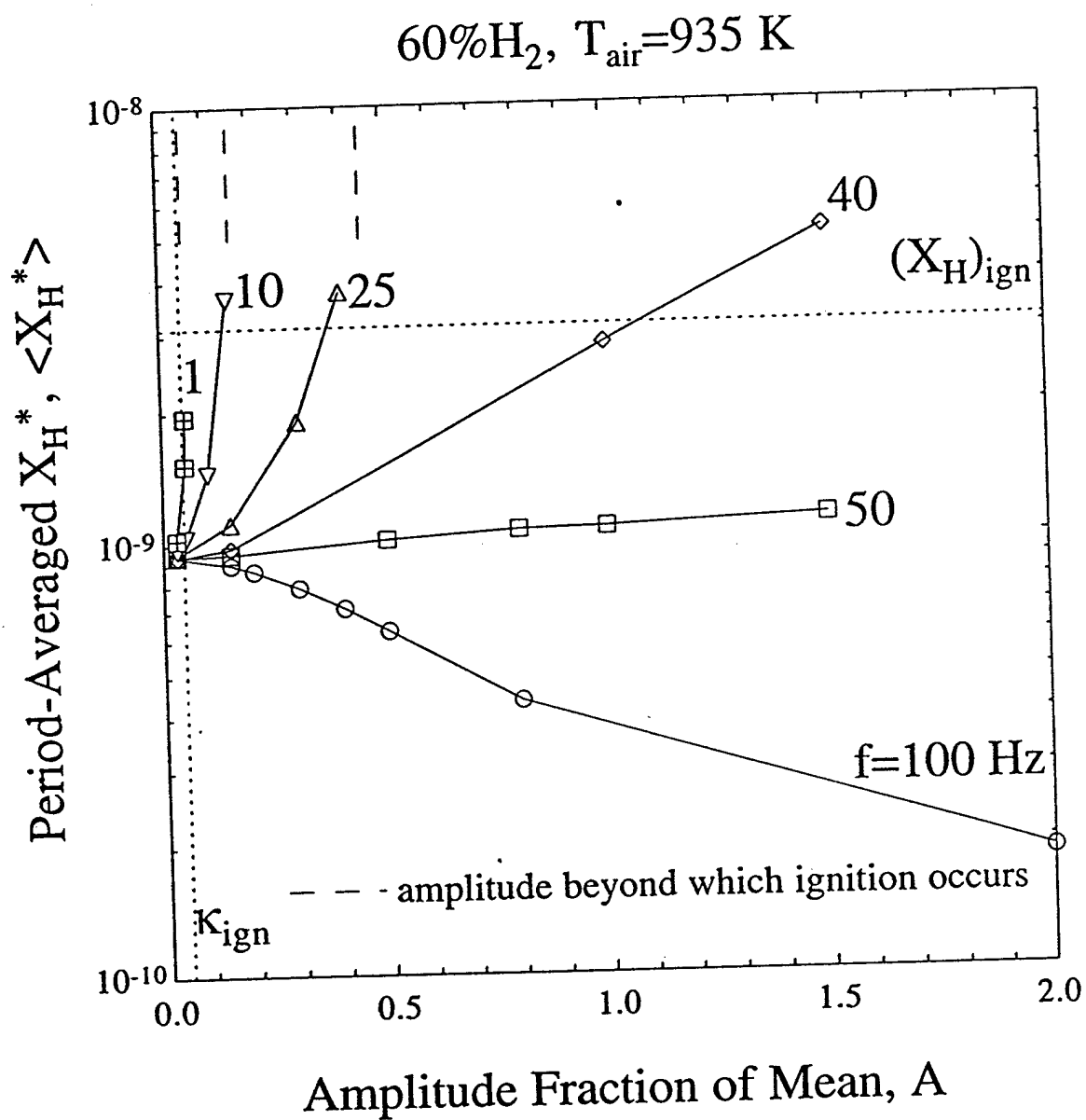


Figure 17

60%H<sub>2</sub>, T<sub>air</sub>=935 K, Impulsive

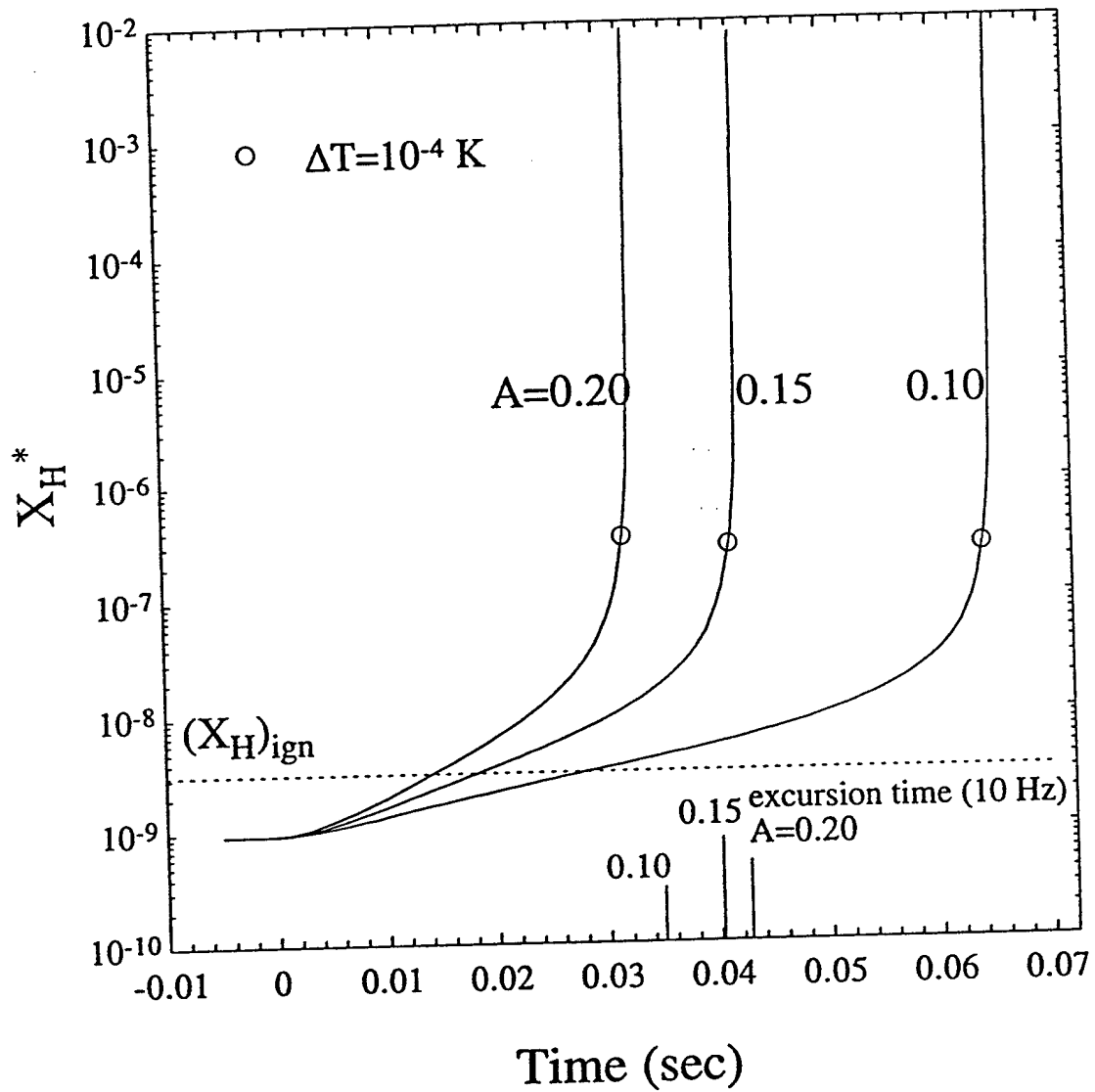


Figure 18

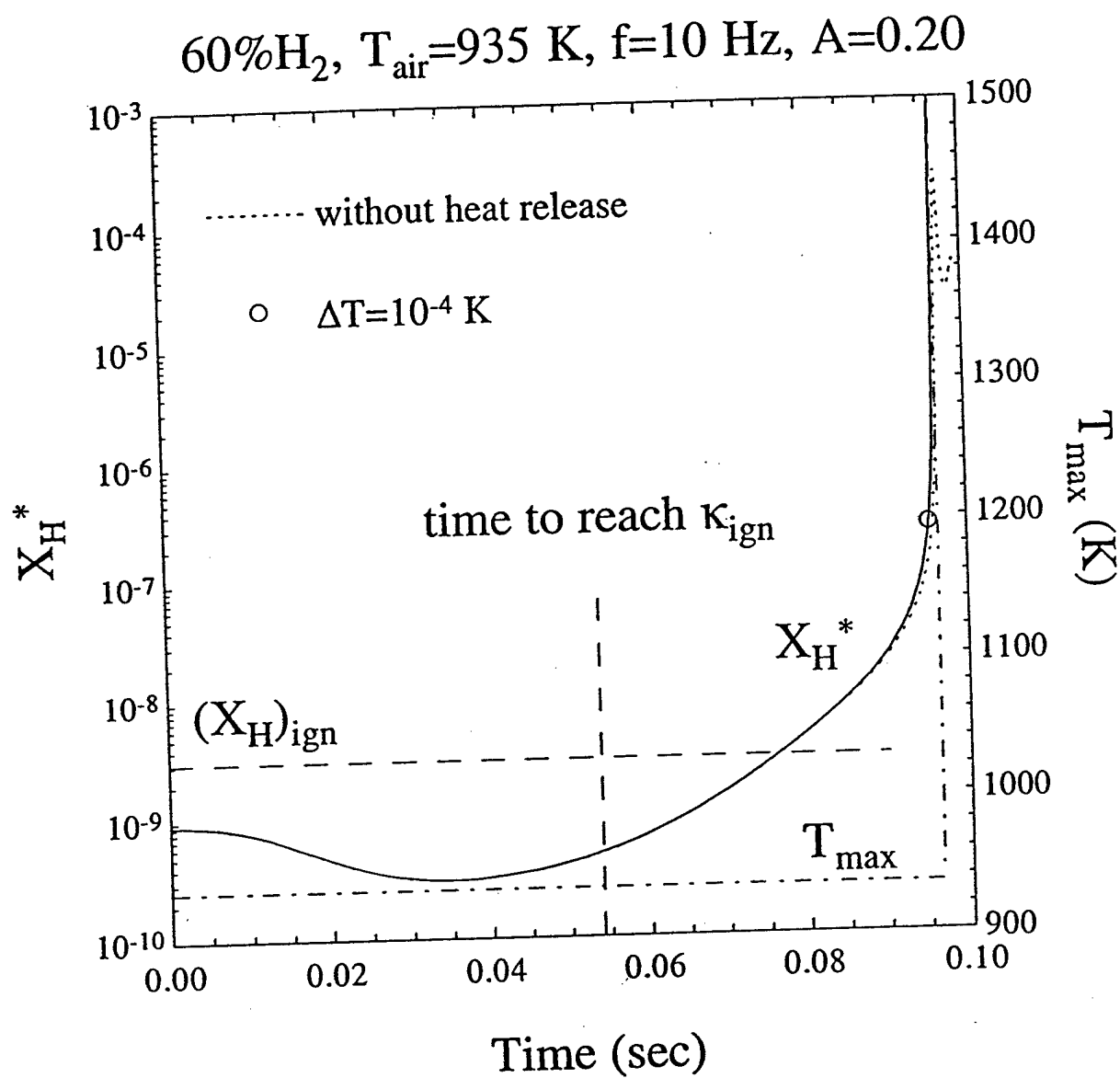


Figure 19

REPORT DOCUMENTATION PAGE			Form Approved OMB NO. 0704-0188	
<small>Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comment regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.</small>				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 5/28/99	3. REPORT TYPE AND DATES COVERED Final		
4. TITLE AND SUBTITLE Ignition in Convective-Diffusive Systems		5. FUNDING NUMBERS DAAH04-94-G-0051		
6. AUTHOR(S) Chung K. Law				
7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES) Mechanical and Aerospace Engineering Department Princeton University P.O. Box CN5263 Princeton, NJ 08544-5263		8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211		10. SPONSORING / MONITORING AGENCY REPORT NUMBER ARO 32293.16-EG		
11. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT  Approved for public release; distribution unlimited.		12 b. DISTRIBUTION CODE		
13. ABSTRACT (Maximum 200 words)  Motivation for this program stems from the Army's interest in understanding and increasing the performance of diesel engines which serve as the main powerplant for its tactical vehicles. Since ignition initiates the entire combustion process in a diesel engine, a good understanding of the ignition process is crucial to the overall performance of the engine in terms of its combustion efficiency as well as the knock and emission characteristics. The ignition event is clearly controlled by the chemical reactions of fuel oxidation and the fluid mechanics of convective and diffusive transport. Most of the studies involved the counterflow configuration created by impinging a cold fuel jet against a hot oxidizer jet, and utilized laser-based experimentation, computation with detailed chemistry and transport, and mathematical analysis with activation energy asymptotics. The study has qualitatively identified some very unique ignition phenomena, and quantitatively determined the states of ignition in terms of the fuel, the heated air temperature, the system pressure, and the strain rate of the flow. The report discusses highlights of the findings and lists the journal articles in which they are documented in detail.				
14. SUBJECT TERMS ignition, diesel ignition, counterflow flames, intermediate-temperature chemistry, hydrogen/oxygen explosion limits, hydrocarbon ignition		15. NUMBER OF PAGES 23		16. PRICE CODE
17. SECURITY CLASSIFICATION OR REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	